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EFFECTS OF RESOLUTION, FIELD OF VIEW AND VEGETATION ON SENSOR ACCESS

Y. MORITA
Radar and Optics Division

JULY 1980

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This report discusses the effects of sensor resolution, field of view and vegetation on geometric aspects of sensor access. Resolution, field of view and vegetation effects on sensor platform operational altitudes and on mapping swath widths are discussed.

Sensors which are considered include line scanners, photographic cameras, television cameras and FLIRs.

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PREFACE

The objective of the minefield detection project is to determine the effectiveness of remote sensing systems and other methods of detecting and identifying mines, minefields, minelaying equipment, or minelaying operations, and to recommend continuing effort on the most promising methods.

Work under the project concerned with each of the concepts to be investigated is being performed in a sequence of four major tasks: (1) identification and screening of promising techniques; (2) preliminary systems analysis and definition of experimental or other data acquisition systems; (3) acquisition of critical data through experiment, literature survey, or access to SCI (Sensitive Compartmented Information); and (4) evaluation of conceptual systems for technical performance and military usefulness.

This is one of a series of reports documenting technical effort and results achieved during the project. This report covers work performed under Task 2, Preliminary Systems Analysis of Candidate Systems.

Dr. J. Roland Gonano monitored the program for MERADCOM, Mr. Henry McKenney was the ERIM Program Manager, and Mr. Yuji Morita performed the analysis.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1
INTRODUCTION

Resolution, field of view and line-of-sight considerations associated with the use of airborne infrared scanners, FLIRs and cameras to locate anti-tank minefields are discussed in this report. The minefields of interest are primarily hastily laid minefields used to deter counterattacks and to protect flanks. Detection systems used must be able to respond rapidly, to search large areas of interest, to obtain the required information and to disseminate the information to the ultimate user. System response time and search rate are functions of the sensor resolution capabilities, the obscuration due to vegetation and the airborne platform characteristics. The effects of resolution, field of view and vegetation height on achievable search swath widths are discussed in terms of geometric relationships.

2
ASSUMPTIONS AND LIMITATIONS

The geometry used in the analysis of a line scanner is shown in Figure 1. A mine is assumed to be on flat terrain. The sensor carrying aircraft is assumed to be flying in a straight line with a level attitude and the sensor is assumed to be stabilized. The vegetation is assumed to be sufficiently dense as to completely obscure a mine if interposed between the mine and the sensor. This assumption should lead to conservative results since foliage density will vary considerably according to the types of plants and depending on seasonal changes. The numbers arrived at should be viewed as boundary values useful in choosing operational conditions of flight. When information on terrain micro characteristics and of the seasonal variation of flora became available, how these factors affect mine obscuration can be assessed.

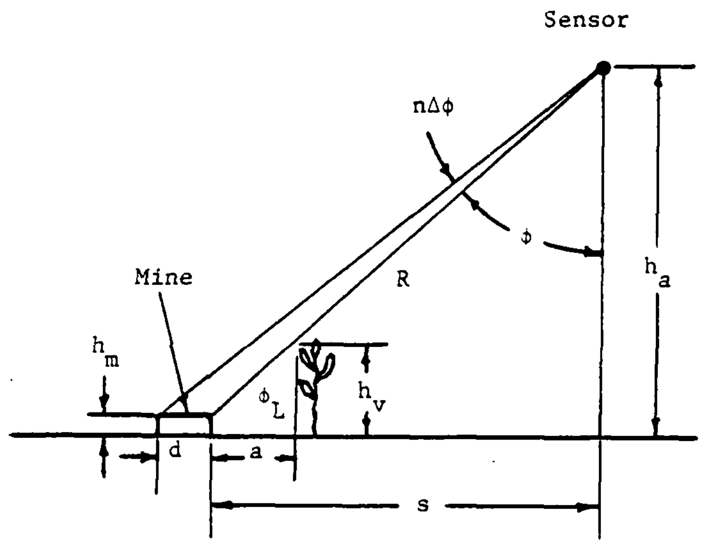


Figure 1. Sensor, Mine and Vegetation Geometry for a Line Scanner

3
GEOMETRIC CONSTRAINTS FOR A LINE SCANNER

In this section, an analysis is given of geometric constraints on the ability of a line scanner to detect mines which are caused by limitations in resolution capability and by line-of-sight limitations. The geometric analysis, as performed, yields information on platform altitude, swath width, and scan angle.

The initial step is to consider how resolution alone affects altitude and swath width. Swath width, as defined in this report, is the useful swath width as restricted only by the resolution and vegetation, and not by the scanner's field of view. The resolution capability of a sensor is denoted by $\Delta\phi$ and n is the number of lines of independent resolution elements required across a target to achieve detection.

Figure 2 illustrates how pixel size on the ground varies as a function of the scan angle. For a given $\Delta\phi$, the pixel dimension normal to the scan direction varies inversely as the cosine of the scan angle while the along-scan pixel dimension varies inversely as the cosine squared of the scan angle. For a unit square pixel at nadir, the along-track dimension of a pixel at 45° scan angle will be 1.41 and the cross-track dimension will be 2.00.

The smallest pixel on the ground occurs at nadir. The pixel size does not increase appreciably at scan angles as large as twenty degrees. Beyond thirty degrees, the along-scan pixel dimension increases rapidly and must be taken into account when considering the number of pixels or lines on a target. The equations given in the following paragraph are developed on the basis that the along-scan pixel dimension is the critical one.

The magnitude of n resolution elements projected across a mine diameter, d, in the scan dimension is $Rn\Delta\phi/\cos\phi$. That this is so

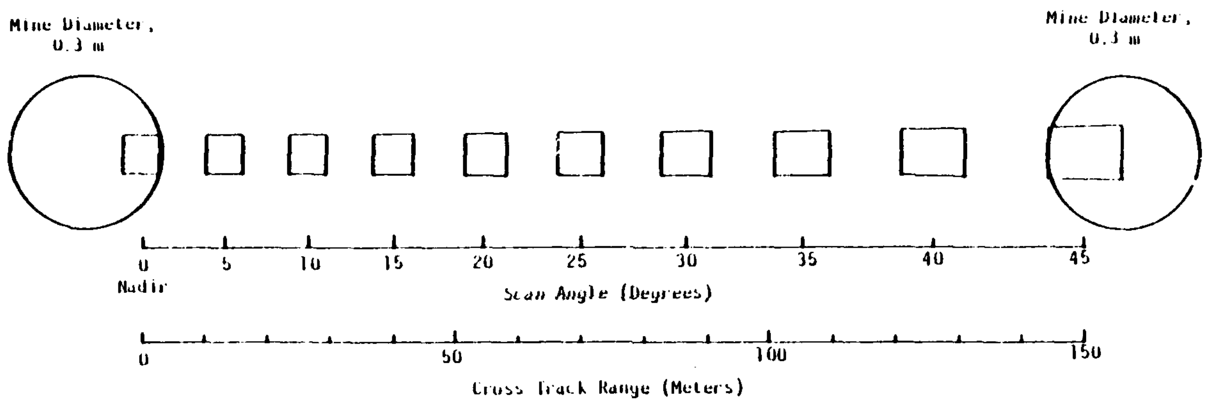


Figure 2. Relative Pixel Size on the Ground as a Function of Scan Angle

Sensor Altitude: 150 m; Instantaneous Field of View,
0.5 mrad x 0.5 mrad

can be seen from Figure 1. The multiple number of resolution elements, $n\Delta\phi$, subtend a length of $Rn\Delta\phi$ at range R for small $n\Delta\phi$. The angle formed between the mine top and the range vector is essentially ϕ. Hence, d, the mine diameter is given by $Rn\ \Delta\phi/\cos\phi$. If this expression is equated to d and solved for the range R, the range can be expressed as

$$R = \frac{d}{n\Delta\phi} \cos\ \phi$$

The altitude and half swath width are respectively

$$h_a = R \cos\ \phi = d \cos^2\ \phi/n\Delta\phi$$

$$s = R \sin\ \phi = d \sin\ \phi \cos\ \phi/n\Delta\phi = d \sin\ 2\phi/2n\Delta\phi^*$$

These two equations describe a locus of points for sensor locations, locations at which there are n resolution elements across the target mine. *An examination of the equations shows that the locus is a* circle offset in altitude so as to be tangent at the mine position (Figure 3). The diameter is given by $d/n\Delta\phi$. For any given sensor location on the circle, it is a simple matter to calculate altitude, swath width, and the scan angle (or field of view). Maximum altitude and maximum swath width are also calculated easily. Figure 4 illustrates how these maximum values change as a function of resolution capability and for two or four lines on a mine.

It has been shown that an observer who can just detect, recognize or identify an object such as a man or a vehicle, can also just resolve one, four, or six-and-one-half pairs of black and white bars, respectively, of a typical photographic resolution chart when one,

*In reality, s should extend to the center of the pixel furthest from the sensor nadir position but still fully on the mine and satisfying the n pixel requirement. The definition of s in Figure 1 is used for convenience in simplifying the equations.

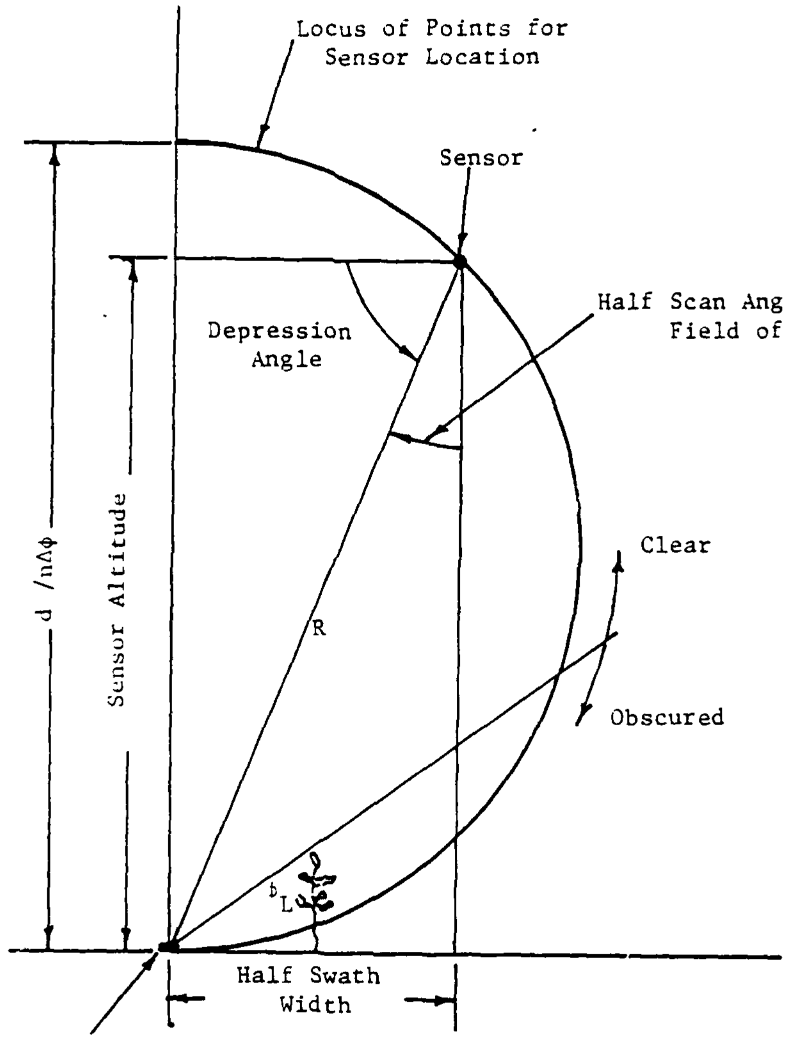


Figure 3. Geometric Definitions and Conditions

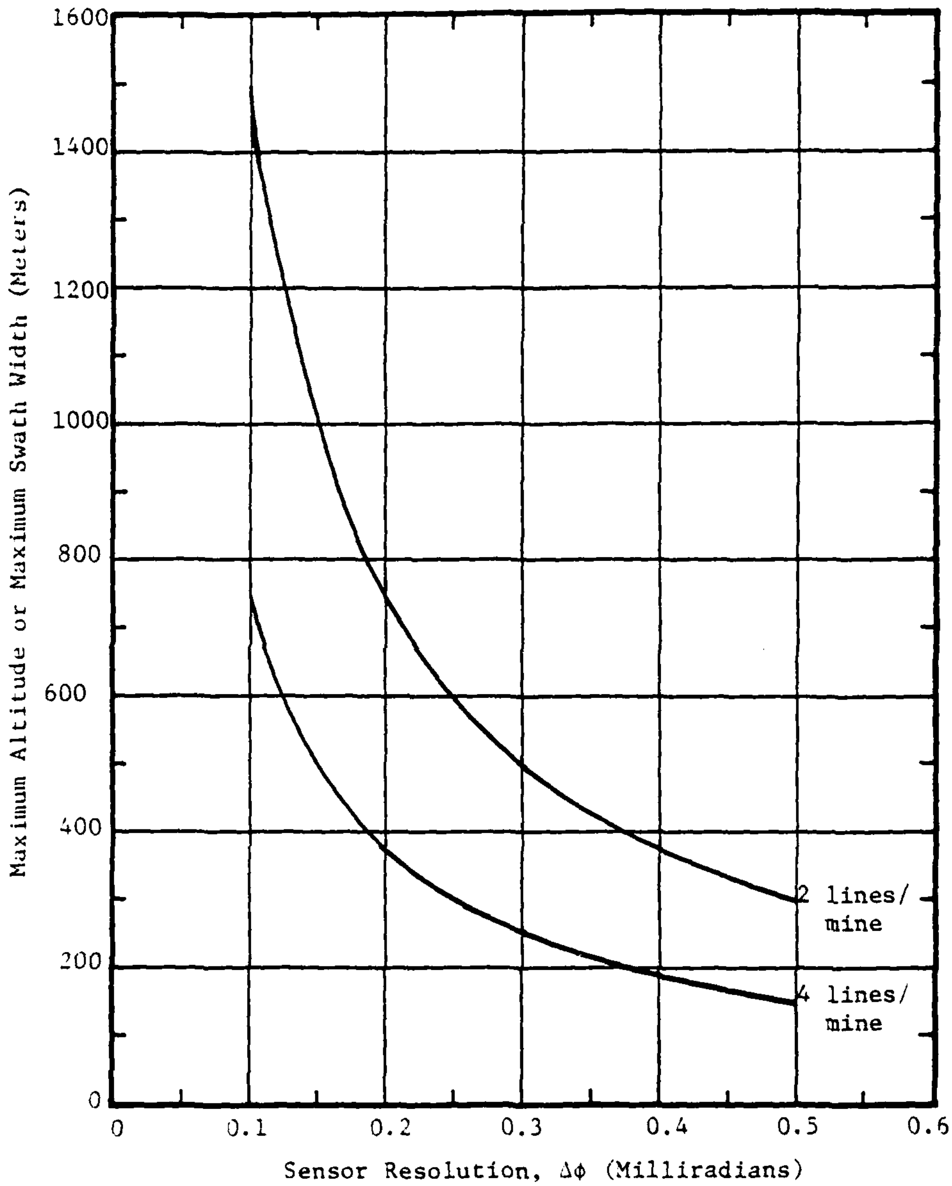


Figure 4. Effect of Number of Lines on Target on Maximum Altitude and Maximum Swath Width

four, or six-and-one-half pairs of such bar widths fit inside the critical (usually minimum) dimension*. The concern here is with mine detection and minefield recognition. This criterion plus past experience has shown that scanners must scan at least two lines or one pair on an object if a mine is to be detected. Four lines on a mine virtually assure detection provided there is sufficient contrast between target and background and little attenuation in the propagation path. Under poor weather conditions, the four line numbers may be a better representation of actual conditions.

Vegetation effects on permissible flight paths can be determined by calculating the limiting half scan angle ϕ_L from the vegetation-mine geometry. The line of sight is assumed to be completely blocked by vegetation. The angle ϕ_L can be expressed as

$$\phi_L = \tan^{-1} [(\ell d + a)/(h_v - h_m)]$$

where ℓ is that fraction of the mine diameter, d, obscured by the vegetation and a is the projection of the distance measured from the mine edge to the point on the plant which just blocks the line of sight, h_v is the plant height and h_m is the mine height. If a is negative, a portion of the plant overhangs the mine (Figure 5(a)). For positive a, there is no overhang (Figure 5(b)). Which situation exists depends on plant type and number of plants in a mine's vicinity. The fraction ℓ can take on any value between 0 and 1. If zero, no overhang can exist and a cannot take on negative values. If one, overhang is complete (or the vegetation is infinitely tall, an impossible condition) and a is equal to -d. For any other value of ℓ between 0 and 1, a can be any positive value or any negative value which is not less than $-\ell$. For example, if ℓ is 0.5, the equation for ϕ_L is

*L.M. Biberman, "FLIR and Active Television: A Comparison of Theoretical and Experimental Data (U)," Journal of Defense Research, Vol. 9, No. 2, Report No. W5765 JDR, Prepared by Battelle Columbus Laboratories for the Defense Advanced Research Projects Agency, Summer 1977, SECRET.

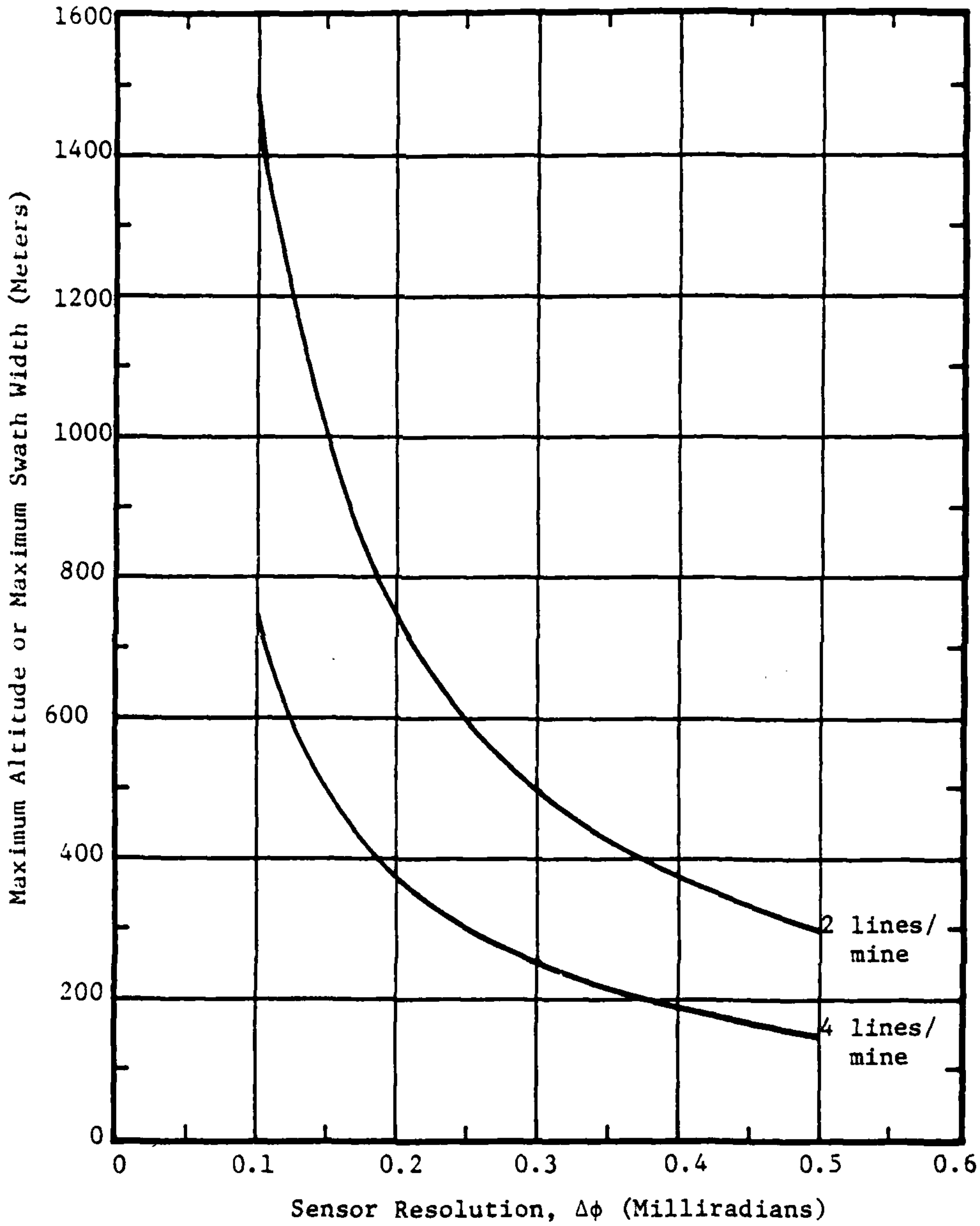


Figure 4. Effect of Number of Lines on Target on Maximum Altitude and Maximum Swath Width

$$\phi_L = \tan^{-1} [(\frac{d}{2} + a)/(h_v - h_m)]$$

$$-\frac{d}{2} \leq a < \infty$$

Specific cases of vegetation effects are plotted in Figure 6 for three different values of resolution and for $\ell = 0$. Spacing a between vegetation and mine is 0.05 m (2 inches). The vegetation limiting radials apply to all three resolution circles. Vegetation with a height of one ft (0.3 m) limits achievable swath width to approximately two thirds of the maximum achievable under ideal conditions. This figure clearly illustrates that sensors should be flown somewhere in the upper half of the permissible locus, preferably as close to mid-altitude as possible (with respect to the theoretical maximum) in order to maximize swath width. The effect of variations in spacing between mine and vegetation is illustrated in Figures 7 and 8. Altitudes and swath widths in Figure 7 are normalized with respect to the locus circle diameter given by $d/n\Delta\phi$. If the spacing between mine and vegetation is reasonably large, as in cases c and d, the achievable swath width is respectable even for vegetation as tall as 0.5 to 0.6 m. These figures underline the importance of at least estimating the nature of plant cover at suspected minefield locations so that reasonable missions can be flown.

In many instances, plants will overhang a mine so that only portions of that mine can be seen. In terms of the limiting angle equation, a takes on negative values. How much of a mine is observable from a given aspect angle is a function of many variables including plant type, spacing, growth season, etc. Any meaningful data must be gathered in the field and the data treated on a statistical basis. Nevertheless, it is instructive to calculate the effects of overhang on the scanner FOV, altitude, and swath width using the geometry of Figure 5a. That fraction of the mine diameter which is not observable is labeled ℓd. Note that that portion of the mine

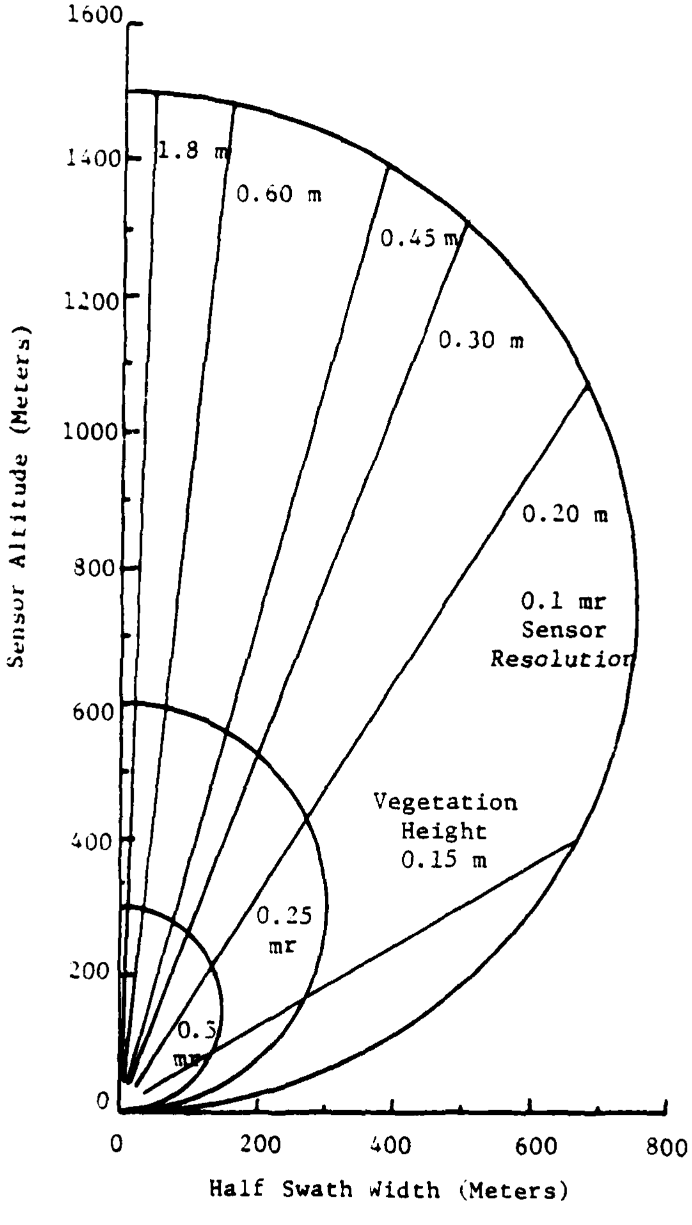


Figure 6. Effects of Vegetation Height and Sensor Resolution on Sensor Altitude and Swath Width.
Spacing Between Mine and Vegetation, 0.05 m

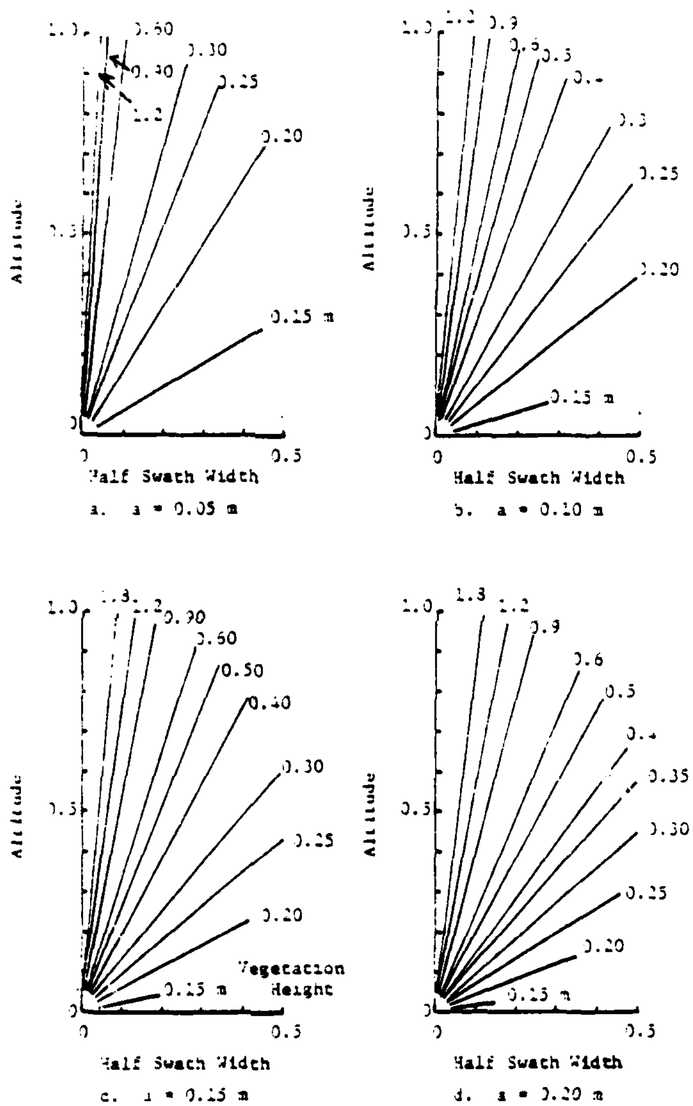


Figure 7. Vegetation Effects on Altitude and Swath Width as a Function of "a"

Altitudes and swath widths are normalized with respect to $d/n\Delta\phi$. "a" is the spacing between mine side and vegetation.

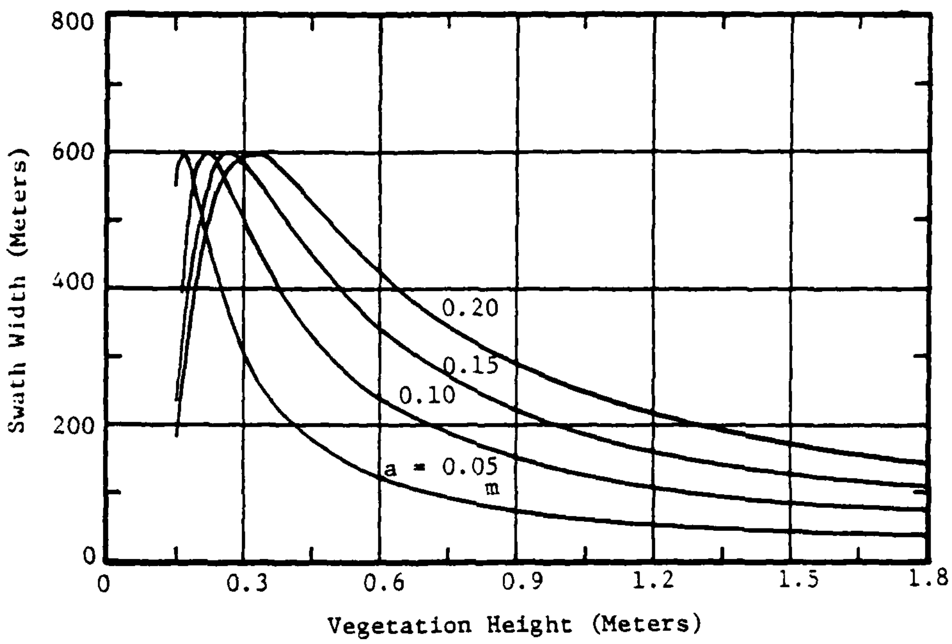


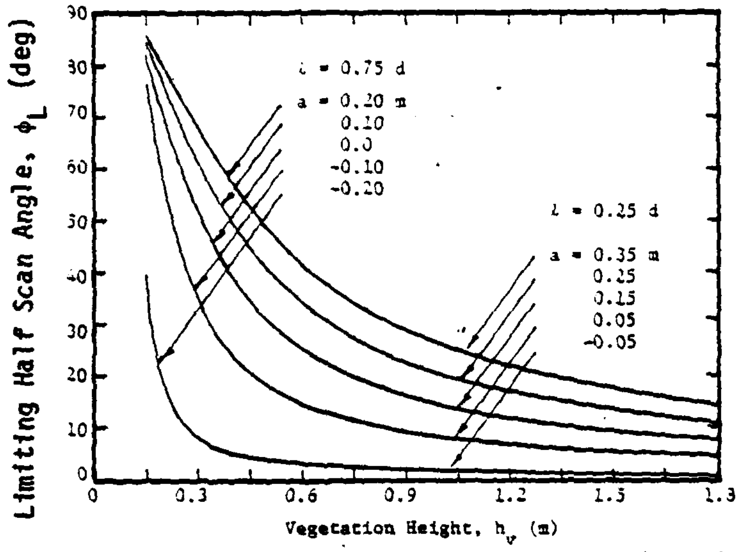
Figure 8. Vegetation Height and Spacing Effects on Swath Width

a is the distance between mine and vegetation. Two lines on the mine and sensor resolution of 0.25 mrad. Scan angles greater than 45° result in swath widths narrower than the maximum width (part of curves to the left of the peaks) and scan angles less than 45° result again in swath width narrower than the maximum width (part of curves to the right of the peaks) which is observable may include a portion which is beneath vegetation overhang on the side opposite the viewing direction. This may not be a valid assumption for passive sensors but the conclusions which can be drawn from the assumed model are sufficiently realistic to delineate reasonable operational limits. Only field data can provide more realistic information.

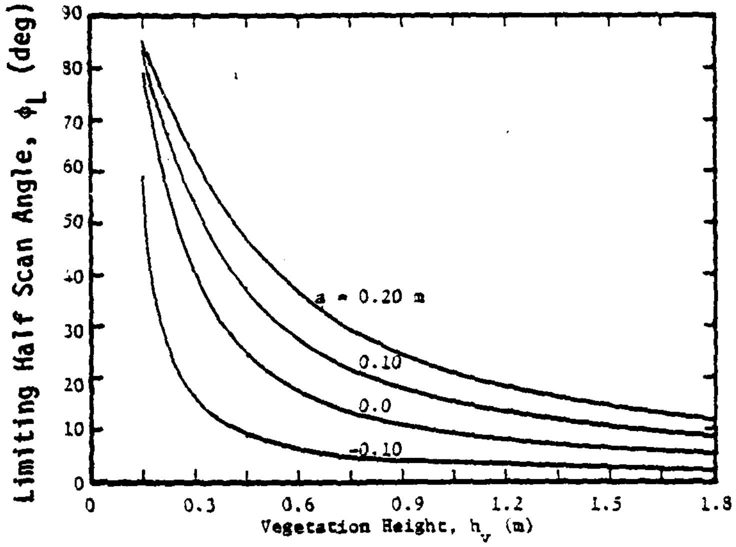
Figure 9 illustrates how overhang or spacing between vegetation and a mine affect the limiting scan angle. If vegetation overhangs a mine, the scan angle is limited to small values. For vegetation even as short as 0.3 m, the useful half scan angle is less than 10 deg. if either one quarter ($\ell = 0.75$) or three quarters ($\ell = 0.25$) of the mine diameter is to be observable. For the former case, the overhang can be as much as 0.225 m. In the latter case, where more of the mine must be seen, the overhang can be maximum of 0.075 m. In both these cases, the limiting half scan angle is zero. As expected, the limiting scan angle increases as overhang decreases and spacing between mine and vegetation increases. Figure 9b illustrates an intermediate case in which half a mine ($\ell = 0.5d$) must be observable. It is clear from these figures that overhang severely bounds the scan angles over which mines can be detected; hence, swath widths will also be decreased substantially with swath width given by

$$2s = \frac{\left(1 - \frac{\ell}{d}\right) d \sin 2\phi}{n\Delta\phi}$$

for ϕ less than ϕ_L.



a. One quarter (ℓ = 0.25 d) and three quarters (ℓ = 0.75 d) of a mine not observable



b. One-Half (ℓ = 0.5 d) of a mine not observable

Figure 9. Effect of Vegetation Spacing on Limiting Scan Angle. Negative values of a refer to overhang.

4
ADAPTATION OF THE ANALYSIS TO FLIR AND CAMERA SYSTEMS

Camera systems and FLIRs produce imagery of an area in time intervals which are short compared to that taken by a line scanner. Assume that if such systems are used for mine detection purposes, their FOVs are pointed at nadir or at small angles from nadir. The parameters of interest for sensor access purposes are resolution capabilities and FOVs. As for line scanners, resolution capabilities determine the maximum altitude at which the sensor can be used and the FOVs determine the area mapped.

Resolution capabilities of cameras are stated in terms of line pairs/mm. If the FOV and the frame size are given, the resolution can be stated in terms of milliradians and the above analytical approach can be applied. As an example, consider the KA-30A framing camera. Its frame size is 4.5" by 4.5" and its field of view is 41° 06' (717.3 mrad) per side. The side length times the resolution in line pairs/mm divided by the field of view in milliradians yields line pairs per mrad, that is, 114.30 mm (40 line pairs/mm)/717.3 mrad = 6.37 line pairs/mrad. In Section 3, the relationship between mine diameter, resolution capability and altitude was derived. This relationship is

$$h_a = \frac{d \cos^2 \phi}{n\Delta\phi}$$

For cameras, ϕ represents half the field of view (Figures 1 and 3). But $n\Delta\phi$ is the angle subtended on the mine. If n is 1 line pair and there are 6.37 line pairs/mrad, the subtended angle $n\Delta\phi$ is 1/6.37 or 0.157 mrad. At $\phi = 41.1°/2$, the altitude is calculated to be 1675.4 m for a 3 m diameter mine. The number of line pairs at the center of the frame will be 1.14. The size of the area imaged is approximately a 1300 m square at this altitude.

The television camera presently planned for use on the RPV is to have a capability to image three FOVs. These are 2.7°, 7.2°, and 20° diagonal FOVs respectively. It can be shown that the swath width, 2s, is equal to

$$2s = 2h \tan \phi = \frac{dm \cos \phi \sin \phi}{n\phi}$$

where h = RPV altitude,

ϕ = half the field of view,

n = the number of resolution lines desired on a target,

m = the total number of resolution lines, and

d = the mine diameter.

For small ϕ, cos ϕ is approximately one and sin ϕ is approximately ϕ. The equation may be simplified to

$$2s = d \frac{m}{n}$$

The swath width is independent of the FOV, directly proportional to the number of lines in the television system and inversely proportional to the number of resolution lines desired on the target. The swath width and the number of lines on a mine for a 350 line system* is illustrated in Figure 10 for the three FOVs. Horizontal resolution is assumed to be the same as vertical resolution. The nominal swath width is approximately 70 m for two lines on a mine. For a given FOV, the swath width becomes narrower as sensor altitude is reduced (Figure 10). Simultaneously, the number of lines on a mine increase. Note that the narrowest FOV permits one to fly higher than the wider FOVs. With a 2.7° field of view, the requirement for two lines on a mine limits maximum altitude above ground to approximately 1860 m. This is advantageous from the standpoint of maintaining communications and from the standpoint of lessening mine

*Minimum requirement of EIA Standard FS330, dated November 1966.

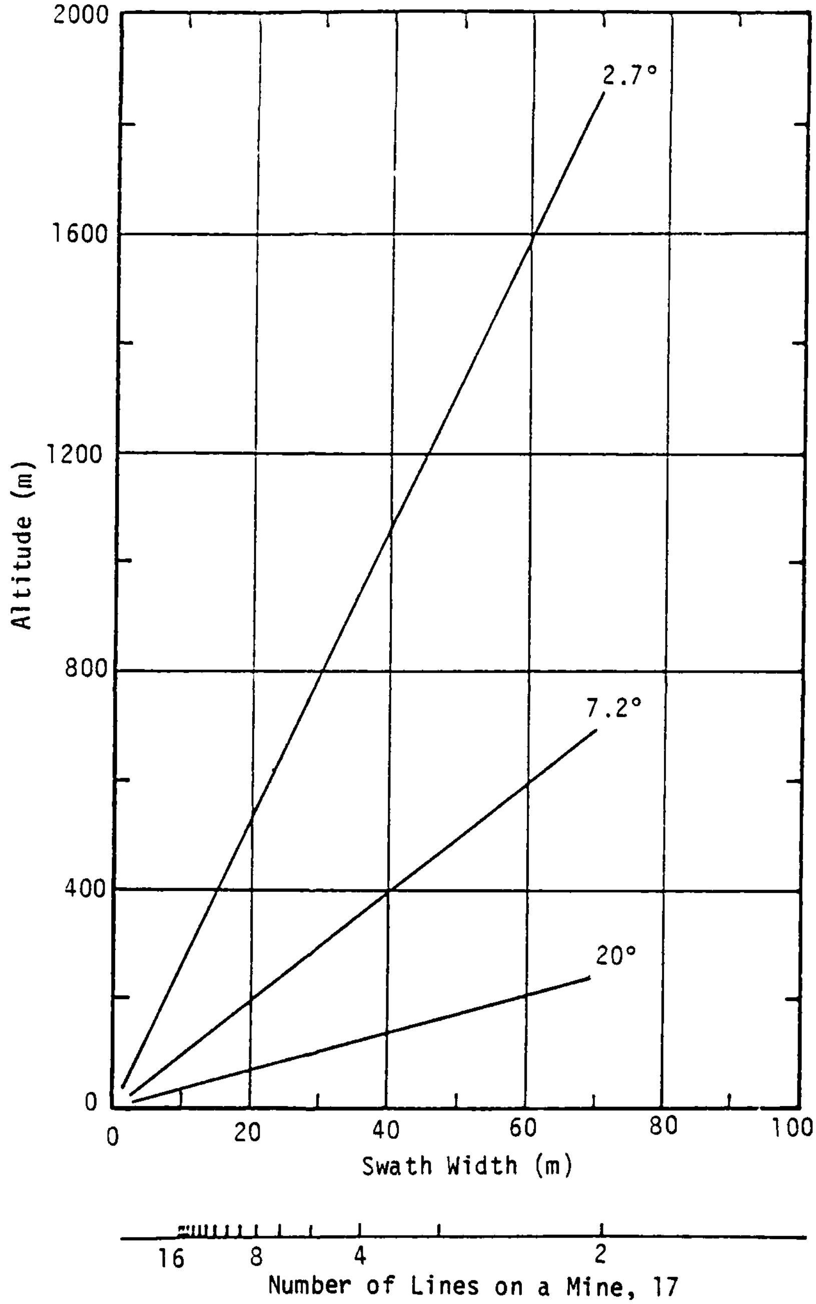


Figure 10. Diagonal Field of View Versus Altitude and Swath Width

Mine Diameter = 0.3 m

obscuration by vegetation. On the other hand, limitations due to cloud ceilings increase with increasing sensor altitude.

If the full resolution capability of 525 lines in the vertical dimension is available, the swath width would be 105 m. An 819-line standard as used by the French would yield a swath width of 164 m.

One of two developmental FLIRs is to be chosen for eventual use with the RPV. The specifications for either of these two units are not yet available to ERIM. Consequently, for the purposes of this report, a FLIR system is postulated. This system is able to point straight down, have the same diagonal FOVs as the television sensor, namely, 20°, 7.2°, and 2.7° with an aspect ratio of 4 to 3, and to have 0.10 mrad resolution in the vertical dimension of the 2.7° FOV. This is tantamount to having a linear array of 280 detectors in the vertical dimension with sweep in the horizontal dimension. The resolution in the horizontal dimension is assumed to be the same as in the vertical dimension. Since the number of detectors is fixed, the resolution decreases as the FOV increases.

Equations similar to those used for calculating the television sensor altitude and swath width for a minimum of two lines on a mine can be used to calculate the same quantities for the FLIR. These values along with the resolution capability are listed in Table 1. As for the television case, swath width remains essentially invariant because the resolution decreases as the FOV increases. Again as for the television case, in good weather, the narrowest FOV should be used in order to minimize line-of-sight obscuration both for the sensor and the data link.

It is of interest to note that the swath width for the postulated FLIR is only 0.8 the swath width for the television system. This is so because the FLIR has a resolution which is 25 percent poorer than the television system. For the 2.7° FOV for both systems, the

TABLE 1
FLIR ALTITUDE AND SWATH WIDTH

Diagonal FOV (degrees)	Resolution (mrad)	Sensor Altitude (meters)	Swath Width (meters)
20	0.75	197	56
7.2	0.27	556	56
2.7	0.10	1485	56

resolution is 0.1 mrad for the FLIR and 0.08 mrad for the television system. If a resolution of 0.08 mrad is assumed for the FLIR with 353 detectors in place of 280 detectors for the 0.1 mrad system, both the FLIR and television systems would have a swath width of 70 m.

5
SUMMARY

Useful sensor bearing aircraft flight profiles to fit operational conditions can be derived in a simple fashion from sensor resolution capability and from consideration of weather, vegetation cover and terrain characteristics. The requirement that a minimum of two pixels subtend a target mine defines a circular locus of points of possible sensor altitude and achievable swath widths with the circle tangent to the ground at the target.

Weather and other constraints permitting, the sensor should be flown at altitudes in the upper half of the circle. Maximum swath width is obtained for sensor scan angles of ±45 deg. with the sensor altitude equal to the circle radius or half of the maximum permissible altitude. If there is heavy vegetation cover, altitude can be increased in order to reduce scan angle limits and to search for mines from angles more directly above the target mines. Increases in altitude will be accompanied by decreases in swath width from the maximum.

If the sensor must be operated at low altitudes because of low cloud ceilings, then the scan angle limits should be increased beyond ±45 deg. in order to maintain swath widths as wide as possible. Only narrow swath widths will be achievable if there is both low cloud ceiling and heavy vegetation cover.

The maximum swath widths attainable are essentially constant for those systems such as television and FLIRs whose resolution capabilities vary as a function of the FOV. Weather permitting and to achieve a given swath width less than the maximum, the use of narrow FOVs allow a sensor to be flown at higher altitudes than if wider FOVs are used.

These systems generally use narrower total FOVs than do infrared scanner systems. Hence, vegetation does not obscure mines as much for television and FLIR systems as for infrared scanner systems operating at their scanning limits.

In this study, the vegetation is assumed to be opaque. In actuality, the vegetation may be less dense allowing partial access to the target mines. The apparent density of the vegetation is affected by the type of vegetation, its degree of maturity, viewing angle, etc. The development of data on vegetational density for typical mine detection scenarios and combat theaters would be a logical sequel to the current effort.

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